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SALTATING PARTICLES, PLAYA CRUSTS AND DUST AEROSOLS AT OWENS (DRY) LAKE, CALIFORNIA

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ABSTRACT

As part of the multinational Lake Owens Dust Experiment (LODE), we have studied the generation of dust storms on the south sand sheet of Owens (dry) Lake, California, an anthropogenically desiccated playa reported to be the single greatest source of particulate matter in North America. During March 1993, we performed an intensive field study including eight significant dust storms, building on our prior work (1978–1984) and preliminary studies (1991–1992). We studied sources and magnitude of coarse saltating particles, the meteorological conditions that allow them to become mobile across the flat playa of Owens (dry) Lake, and how the motion of saltating particles across different types of playa surfaces results in the generation of PM_{10} dusts (aerosol particles smaller than 10 μm aerodynamic diameter). Saltating grains of lacustrine sand and broken crust abrade and disaggregate the playa surface into fine aerosols, and the resulting PM_{10} concentrations recorded during major dust storms are among the highest ever recorded in North America. On 23 March 1993, we measured a 2 h concentration on the playa of 40 620 $\mu g\,m^{-3}$, as far as we can determine the highest ambient PM_{10} value ever recorded in the U.S.A. Abrasion of salt-silt-clay crusts by saltation is shown to be responsible for all but a small part of one dust storm. The quantity 'sand run', saltating particle transport multiplied by wind run, is shown to be very closely correlated with dust aerosol concentration. Finally, we have established that on-lake bed studies are essential for quantitative prediction of dust events on the Owens (dry) Lake bed, despite the difficult conditions encountered.

KEY WORDS playa; dust; PM_{10}; Owens (dry) Lake; crust; saltation; sand run

INTRODUCTION

Owens Lake is the terminal lake of the Owens River, located in southeast-central California (Figure 1) in the valley of the same name. Since 1926, there has been near-continuous diversion of surface and ground water from the Owens River basin into the Los Angeles Aqueduct (Nadeau, 1950), leaving Owens Lake without its primary source of water. Within several years the 280 km^2 terminal lake evaporated, leaving an alkaline, saline playa. The depth to moisture is typically only a few centimetres below the dry surface, due to recharge by aquifers derived from untapped watersheds of the Sierra Nevada and the White-Inyo mountain ranges, as well as the deep brine pool beneath the playa. This feature, coupled with surface flooding during the winter and spring, results in the formation of crusts on the eastern and southern sides of the lake bed that are extremely vulnerable to wind erosion by abrading saltating particles (Barone *et al.*, 1981; St Amand *et al.*, 1986; Cahill *et al.*, 1994; Reid *et al.*, 1994).

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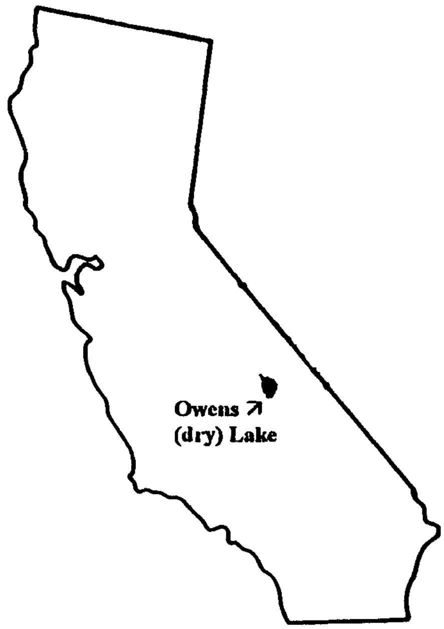

Figure 1. California map showing location of Owens (dry) Lake

There have been reports of dust storms from the dry bed of Owens Lake since it was desiccated, to the point that the term 'Keeler fog' was coined for the dry dust events at the small town of Keeler on the north-east shore of the lake. The characteristics of 'Keeler fog', namely that it did not scratch paint but could penetrate the smallest crevice and contaminate dwellings, are in full accord with later measurements showing that the particles are much finer than those produced by most other natural dust storms (St Amand *et al.*, 1986; Reid *et al.*, 1994). Since 1986, the United States and State of California environmental protection agencies have regulated and set standards for PM_{10} (airborne particles with aerodynamic diameter less than 10 μm). PM_{10} aerosols are sufficiently small that they can be transported great distances, and can be inhaled deeply into the human respiratory tract creating a health hazard. In most years the highest 24-h-average PM_{10} readings in California occur downwind of Owens (dry) Lake, at the edge of eastern Sierra Nevada and Great Basin. Owens (dry) Lake is the largest single source of fugitive dust (dust composed of geological materials released into the atmosphere by human action—in this case, water diversions that drained a lake) per unit area in the United States, with production estimates ranging up to millions of tonnes annually (Gill and Gillette, 1991).

The nearby settlements of Keeler, Darwin, Lone Pine and Coso Junction are frequently impacted by dust, and the growing cities of Ridgecrest/Inyokern (90 km south of the playa, population *c.* 60 000) are impacted a number of times per year. Near Owens (dry) Lake are numerous areas sensitive to visibility degradation and dust deposition, including Sequoia, Kings Canyon and Death Valley National Parks, several national forests and numerous designated wilderness areas. The dust plumes have a pronounced effect on visibility on the United States Naval Air Weapons Station, China Lake, shutting down range operations up to eight times per year and resulting in economic losses of many millions of dollars.

A study commissioned by the California State Lands Commission, owner of the playa (WESTEC, 1984) identified several dust-producing regions on the eastern and southern ends of the lake bed (Figure 2). When the lake bed is not wet, these regions generate dust when wind speeds several metres above the playa surface exceed approximately 7 m s^{-1}. Because of topographic forcing by the Sierra Nevada and White-Inyo ranges, winds over the lake bed during major events tend to blow roughly north or south. Lake bed sediment and sand from nearshore deposits provide sufficient saltating particles to sandblast the crust and generate extensive PM_{10}.

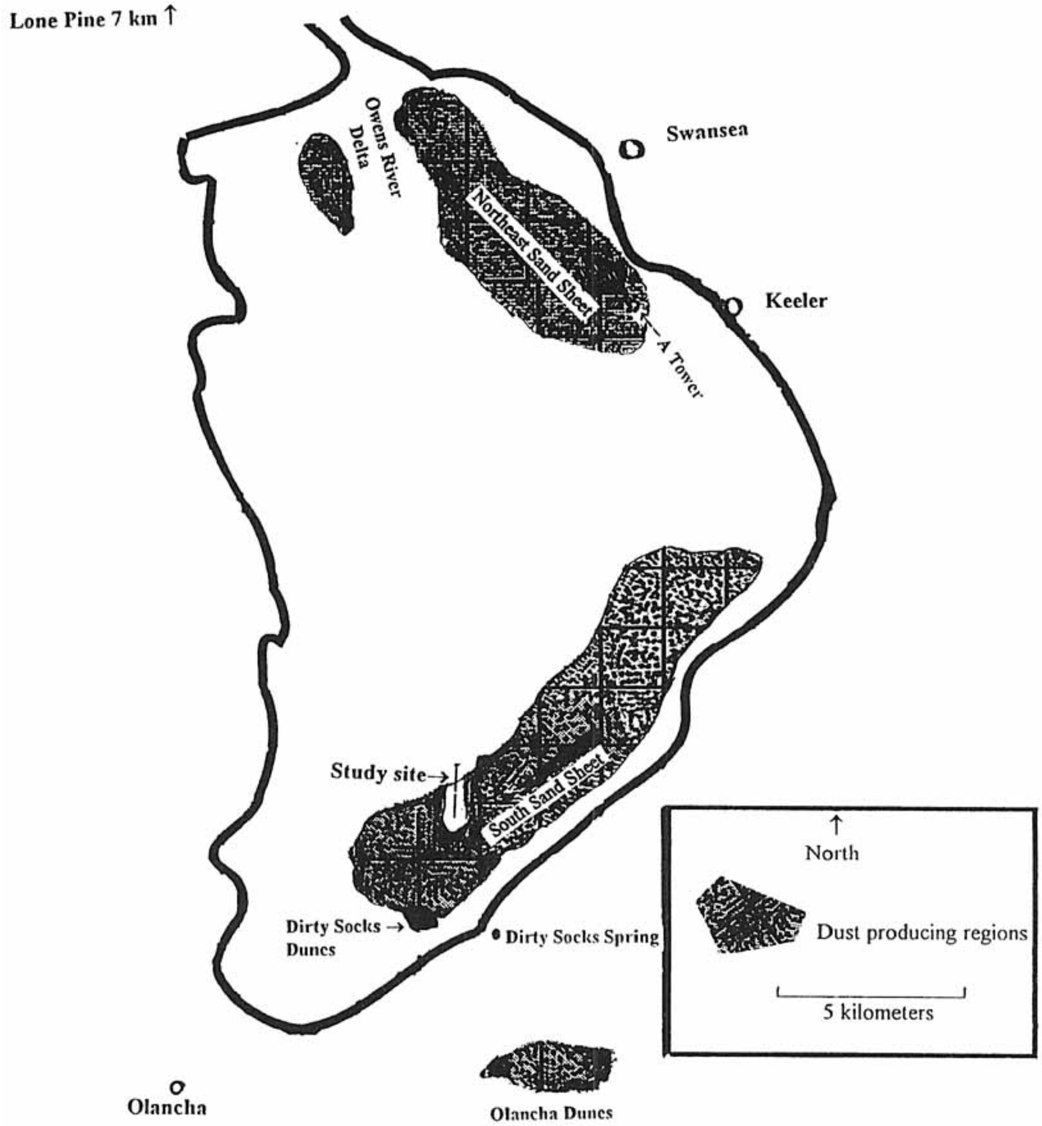

Figure 2. Location map of Owens (dry) Lake; major dust-producing regions are shaded

The largest and most frequent dust storms tend to occur in the spring and fall, though large events may occur during any month. Previous studies investigated dust plumes transported to the north (Barone *et al.*, 1979, 1981) and south (St Amand *et al.*, 1986; Reid *et al.*, 1994) of the dry lake, respectively. St Amand *et al.* (1986) showed that atmospheric loading during major dust events was equivalent to $2\,\mathrm{t\,km^{-2}}$, with plumes having concentrations as high as $2600\,\mu\mathrm{g\,m^{-3}}$ some 100 km south at the U.S. Navy's China Lake facilities. Because of their small size and the extreme turbulence in the boundary layer, Owens (dry) Lake dust particles can be transported long distances. This has been confirmed by both St Amand *et al.*'s (1986) use of satellite imagery, in which plumes were observed to be transported 250 km to the south, covering over $90\,000\,\mathrm{km^2}$, and the results of Reid *et al.* (1994), which laid the groundwork for the present study.

The earlier studies identified that particulate mass levels were extremely high on those days (roughly 11 per cent) that showed any dust at all, and sand motion across the crust was a major factor in dust generation.

The present study, part of the international Lake Owens Dust Experiment (LODE, March 1993) was designed to answer unresolved questions from earlier work, relate problems at Owens (dry) Lake to similar situations such as Mono Lake (a playa lake approximately 200 km northwest of Owens (dry) Lake), that also experience dust storms (Kusko and Cahill, 1984; Cahill and Gill, 1987), and help to lay the scientific groundwork for dust mitigation efforts of Great Basin Unified Air Pollution Control District (GBUAPCD), the State Lands Commission, and others (Gill and Cahill, 1992a; Cahill *et al.*, 1994; Ono *et al.*, 1994).

MATERIALS AND METHODS

The conditions in which the study was performed were formidable, with wind gusts above 40 m s^{-1} blasting tonnes of sand across the playa, generating PM_{10} levels as high as 40 620 μg m^{-3} (over a 2 h sampling period). New instruments had to be developed and tested to handle these conditions, while other types were modified and adapted.

Meteorological measurements

The GEOMET meteorological tower located on the south sand sheet of the Owens (dry) Lake bed is a self-contained, solar-powered monitoring instrumentation package that transmits meteorological and soil flux data to a satellite (McCauley *et al.*, 1984). The data are collected routinely by the Desert Winds Project of the Astrogeology Branch of the U.S. Geological Survey. The GEOMET uses a HANDAR meteorological measurement system with anemometry at three levels to measure wind profiles, temperature profile, soil temperature, precipitation and airborne soil flux using the Sensit instrument (Stockton and Gillette, 1990) and a BSNE wind erosion flux collector (Fryrear, 1986).

Hourly horizontal wind speed and direction, temperature and humidity data were collected at four meteorological towers maintained by the GBUAPCD. These towers are located around the lake bed at the towns of Lone Pine, Keeler and Olancha, and at 'A-Tower' on the playa itself. A variety of other standard meteorological towers from various manufacturers were employed on the playa in this study. All towers employed contained wind speed/direction sensors at least 3 m above the ground, and temperature/humidity probes.

Generation of PM_{10} dusts

Saltating particle transport and production on the study plot on the lake bed was determined using BSNE samplers (Fryrear, 1986). BSNEs were emplaced at ten locations along a 1·2 km long north–south line on the flat, completely unvegetated south sand sheet (the primary dust storm initiation region) of Owens (dry) Lake, centred approximately 3 km northwest of the GEOMET site. At each location, individual BSNE collectors were placed with inlets at elevations of 10, 20, 30, 50, 60 and 100 cm above the playa surface. After each dust event, each BSNE was emptied and the mass of saltating particles collected was determined gravimetrically.

Direct measurement of PM_{10} dusts in the presence of high winds and moving sand required design and construction of a new portable aerosol sampler, the portable filter sampler (PFS). The PFS is a modified version of the stacked filter unit (SFU), which was designed by the first author's group and has been used extensively in many air quality studies (Cahill *et al.*, 1990). The SFU inlet was designed to provide a PM_{10} size cut at wind velocities up to 7 m s^{-1}. At Owens (dry) Lake, measured wind speeds have exceeded 30 m s^{-1}, so the inlet required modifications in order to retain its effectiveness. We added a wind baffle in order to reduce the wind velocity to a level at which the inlet can provide a PM_{10} cut point (velocity times 0·11). Cassettes containing 47 mm Teflon filters were installed in the sampler just prior to sampling to reduce the possibility of contamination by fugitive dust. The pump, battery and programmable controller were located in a sealed sampler module. Care was taken to avoid exposing the filters in the cassettes to contamination, and the cassettes were stored in sealed bags prior to and after sampling. Despite these precautions, artifact levels were higher than we expected due to the invasive nature of the dusts and the conditions on the lake bed. During the experiment, we also observed a deterioration of the pumps due to erosion of the seals, which led to increases in the potential error of individual aerosol measurements (uncertainty of individual measurements shown in Figure 5 and Table III was approximately 5 per cent through the first measurement of 11 March,

but we estimate that by 17 March it had risen to approximately 20 per cent, and by the 23 March it approached 40 per cent). Quality assurance testing after the samplers were returned from the field indicated, however, that the samplers performed adequately throughout the study (Cahill *et al.*, 1994).

Two aerosol measurements at each meteorological station site were taken in this study. Each of these sites also had a set of BSNE saltating particle monitors (Fryrear, 1986). One PM_{10} sampler inlet was located at 60 cm above the playa, and the other at 3 m. These samplers were affixed to the meteorological towers and run for sampling periods of 1 to 2 h. A total of 42 samples were taken during the study, all of which were analysed for mass concentration. Aerosol mass was determined gravimetrically using the quality assurance protocols of the Interagency Monitoring of Protected Visual Environment (IMPROVE) programme, a joint programme of the U.S. National Park Service, Environmental Protection Agency, Forest Service, Bureau of Land Management, and Fish and Wildlife Service (Eldred *et al.*, 1990).

Playa surface conditions

In order to select an appropriate study site typical of a major dust initiation area, and monitor typical surface conditions and changes through time, we carried out extensive field reconnaissance on and around the playa of Owens (dry) Lake on an intermittent basis over three annual cycles from 1991 through the spring of 1994. Discrete playa surface landforms were identified, with attention being paid to crusted playa surfaces, regions of loose, coarse clastic particles (sand sheets and dunes), sites where plumes of blowing dust were observed to initiate, and especially the zones of interface between these environments. During the intensive field study period (March 1993), playa surface conditions at and around the experimental sites were carefully monitored before, during and after each dust event. The percentage area of surface remaining as saline crust was estimated from photographs taken at each site over the course of the intensive period. The areas were estimated by placing known-area masks over the crusted surfaces and summing the area of the masks with respect to the total area. Estimated error for this procedure is about 10 per cent.

Dust transport monitoring

A small motor home was outfitted for aerosol characterization. Dust aerosols were sampled from two stacks at a height of 5 m above the surface (1·5 m from the roof of the vehicle). Vehicular instrumentation included a DRUM impactor (Cahill *et al.*, 1987; Raabe *et al.*, 1988). A secondary PFS was run side by side with the DRUM as a direct measure of gravimetric mass and for quality assurance purposes.

When dust events occurred, the vehicle was driven into the main plume and proceeded to sample the source aerosol for at least 10 min. Existing roadways allowed for sampling within 1 km of the lake bed. A hand-held anemometer gave an estimate of wind speed and direction.

Automatic cameras were placed in two locations. The first was located at an elevation of 1000 m above the lake bed, 6 km northwest of the town of Keeler. The field of view covered 85 per cent of the lake bed. The second camera was placed alongside the south side of the lake bed to aid in measuring plume rise and thickness. This camera was triggered every half hour during daylight storm periods. These systems used a Canon EOS 650 body with a 28 mm lens. A battery-operated intervalometer allowed for as many as 20 photographs per day.

RESULTS AND DISCUSSION

The LODE programme took place under ideal natural conditions. Meteorological conditions were characterized as the first 'normal' spring after six years of drought. Average daily dust concentrations at Keeler in March 1993 were in the same range as those during the non-drought period of 1979–1983 (Table I). The study began with an efflorescent surface that was deflated during part of one dust event, leaving behind a salt-silt-clay crust which degraded through several major dust storms, only to be re-established after the last storm by the rains of 25 March. The sampling equipment remained operational through late March 1993; only one major dust storm (24 March) escaped complete scrutiny, largely due to intolerable conditions on the playa for both personnel and equipment.

Table I. Distribution of PM_{10} concentrations ($\mu g\,m^{-3}$) at Keeler, east shore of Owens (Dry) Lake, 1979–1983 (after Kusko and Cahill, 1984) vs. March 1993 (GBUAPCD data). 1979–1983 data are converted from total suspended particulates to PM_{10} by multiplying by 0·545 (Hardebeck, pers. comm., 1993): March 1993 data are from a PM_{10} sampler

Category	1979–1983	March 1993
Avg. 24 h PM_{10} concentration, highest 5% of all days	653	512
Avg. 24 h PM_{10} concentration, highest 11% of all days	343	394
Avg. 24 h PM_{10} concentration, remaining 89% of all days	14	34
Total days sampled	327	18

Meteorology

The lower Owens Valley has a bidirectional regime of prevailing winds near the surface, as a result of the confining topography. Four distinct types of storms were observed during the study period. The 11 March storm was a 'post-frontal passage' storm. With the passage of a weak cold front, ridge building gives rise to moderate to high northerly winds for about 6 to 12 h. The 17 March storm was produced by rapid cold front passage. Strong morning southerly winds formed and transported large amounts of dust northward. At approximately 11 a.m. the front passed and the flow rapidly shifted to a strong northerly wind, 'backwashing' the dust from north to south into Lone Pine, Keeler and Olancha. The 24 March event represented a stalled, strengthening low giving rise to southerly winds for three days at a time. The largest dust event observed was produced by this flow pattern. Significant dust was generated with the southerly wind on 23–25 March. In the morning of 25 March we observed dust being generated on the playa even during a moderate rain shower. In addition, weaker mesoscale afternoon mountain-valley winds frequently developed, producing minor dust events. These plumes tended to disperse within 10 km of the lake bed. The dust storm of 18 March 1993 is typical of these events, in which automatic camera photos coupled with meteorological data taken on the lake bed showed extremely complicated flow patterns over the playa; dust production was intense but extremely localized.

Sources of saltating particles

Sedimentology and geomorphology of the playa surface. The Lake Owens Dust Experiment built on earlier fieldwork on the Owens (dry) Lake bed by ourselves and others (Barone *et al.*, 1979, 1981; Kusko and Cahill, 1984; St Amand *et al.*, 1986, 1987; Gill and Gillette, 1991; Cahill *et al.*, 1993; Reid *et al.*, 1994), as well as two years of field reconnaissance before the beginning of the intensive dust monitoring study in 1993. This work, coupled with close observation of playa surface conditions at each dust sampling site during and after the spring 1993 field period, have allowed for a basic understanding of the geomorphic state of the Owens (dry) Lake playa through typical annual cycles, and how earth surface conditions on the lake bed influence the availability of particles for aeolian erosion. Detailed textural information for the LODE experimental site is presented elsewhere (Gillette *et al.*, 1996): this section provides an overview of playa surface conditions and materials in the study area.

The surface of Owens (dry) Lake is soft in winter, when it is wetted by winter rains and becomes muddy or covered by a thin sheet of water. Under these conditions, dust storms are generally reported to be small and

infrequent, as shown by the statistical record of PM_{10} at Keeler (GBUAPCD, unpublished data). During dry periods in winter and into very early spring, an efflorescent crust produced by discharging saline groundwater, typically rich in mirabilite and other evaporites (St Amand *et al.*, 1987) covers the surface. In early spring, the efflorescent salts covering the lake bed give it a snow-covered appearance until they are blown away. Subsequently, and through much of the spring, the dust-producing areas of the lake bed are covered by the remaining salt-silt-clay crust. The crust is broken up and degraded into a rough surface by the effects of desiccation, and abraded by saltating particles. Large areas of the lake bed are covered by a layer of rippled sand generally several centimetres deep.

The playa surface is generally quite hard in summer and autumn, in areas not covered by loose mobile sands. A few summer thunderstorms dropped significant precipitation on the lake bed, wetting the silt-clay surface which dried into a hard crust; we call this the 'cemented crust' in order to distinguish it from the 'efflorescent crust' of late winter and the 'salt crust' of spring, which is in reality a mixture of salt, silt, clay and sand. Although the playa may be very moist several centimetres below the surface throughout the year, the surface layer is dry. As the autumn months are typically free of precipitation but often characterized by strong winds, the crust again becomes degraded by moving sand. Dust episodes become more frequent in this period.

As long as the surface of the playa is stabilized by a non-efflorescent crust and the integrity of the crust is maintained, the formation of dust is discouraged, as shown by studies of Owens playa crusts in the wind tunnel (Gillette *et al.*, 1982). When the crusted surface is disturbed by moving sand, aerosols are generated. The northeast and south sand sheet areas are both primary aerosol production zones and possess an abundance of loose sediments. The centre of the lake bed keeps its hard, undisturbed crust of sediment or salt intact during the dry season because there is little or no sand moving across it. Other nearby playas such as Panamint Valley are not significant sources of PM_{10} because the sand deposits are stabilized by vegetation and the water table is too deep to allow saline groundwater discharge (Gill and Cahill, 1992b).

We characterize the crusted playa surfaces in the primary dust production zone as follows.

1. Efflorescent, very fragile crystalline crust that grows from evaporation of saline groundwater discharging onto the surface in late winter. White in colour, the playa appears to be snow-covered when this material is extensive. On the south sand sheet, this crust was destroyed and removed by wind erosion in about 2 to 3 h on the morning of 11 March 1993. Its impact on PM_{10} dusts was not documented, but during this event we observed fragments which appeared to be too large to directly loft into fine aerosols. After the rains of 25 March 1993, a new salt-silt-clay crust was formed. Within a few days thereafter, a new efflorescent crust developed atop it, only to be eroded quickly by saltation abrasion in April.
2. A salt-silt-clay crust that underlies the fragile efflorescence. This crust is massive, relatively hard, whitish-grey to greyish-white in colour, has a rough, heaved-appearing surface and is cemented by evaporite minerals (which are visible in discrete masses). The salt-silt-clay crust is susceptible to saltation abrasion; at the study site, we observed it gradually erode from 11 to 24 March on a storm by storm basis, and then be reformed after late March rains. In areas in which a non-efflorescent crust was intact, little dust was generated. As the salt-silt-clay crust was degraded, large areas broke into polygons surrounded and underlain by loose clastic materials. These areas were easily suspended by winds and formed the major blowing dust sources during the intense March storms, with a saltation–erosion mechanism generating particles as fine as $0{\cdot}3\ \mu m$ diameter (Cahill *et al.*, 1994).
3. A cemented crust that forms after rain storms in late spring, summer or fall. This crust is very sturdy, buff/beige to light brown in colour, and has a smoother surface lacking the microtopography of the salt-silt-clay crust which precedes it. The 'cemented crust' forms above sand/salt mixtures, is less saline (lacking visible salt crystals), is cemented primarily by clay, will even support motor vehicles (in some cases) and is relatively resistant to wind erosion. Until the 'cemented crust' was, in turn, eroded by saltation abrasion, dust production was sharply curtailed even in high winds. We observed the slow erosion of this crust on the south sand sheet through the generation of new loose sands, starting near the Dirty Socks Spring dunes and spreading northward during summer and autumn 1993.

There are other types of crusted playa surfaces around Owens (dry) Lake, such as silty crusts observed near

where alluvial fans meet the playa edge and in the Owens River Delta, and the bedded evaporite deposit of the central area of the lake bed. Neither were common at or near the study site.

Generation of saltating particles. We believe that the causative mechanism for well over 95 per cent of the Owens (dry) Lake dust events observed during the period of this study is the release of fine (PM_{10}) particles from the playa surface upon impact by saltating coarse particles. This phenomenon was supported by the data documented in forerunner projects at Owens and Mono Lakes (Barone *et al.*, 1979, 1981; Kusko and Cahill, 1984; Cahill *et al.*, 1986).

Saltating particles on the lake bed are formed by a number of processes. The saltation process itself creates new sand-sized particles out of the crust as it breaks up the surface. Wind tunnel tests by Gillette (WESTEC, 1984) indicated that rare, extreme wind events (sustained winds of 25 to 50 m s^{-1}) over the lake bed can eventually break down the crust into constituent particles. However, most saltating particles are derived directly from existing major sand deposits along the edges of the playa.

Several areas have been previously identified as primary source regions of saltating grains on the playa of Owens (dry) Lake (WESTEC, 1984; Aerovironment Corp., 1992). Our field observations confirmed these regions as the significant zones of moving sand and thus, not surprisingly, major dust storm genesis areas (Figure 2).

The south sand sheet, located on the southeastern part of the lake bed north of Dirty Socks Spring, is one such area. The sand is supplied to this area primarily by the unstabilized Dirty Socks Dunes and a ring of lacustrian sediments on the outer part of the Owens playa. A small amount of sand may be derived from the Braley, Cartago and Ash Creek alluvial fans draining the Sierra Nevada. On-site observations since 1991 have shown that during periods of sustained strong southerly wind (speed at 2 m height on the order of 15 m s^{-1}), waves of sand stream off the Olancha Dune complex—located several kilometres south of the modern-day playa—and onto the south sand sheet of Owens (dry) Lake, intensifying the formation of dust plumes. Although the area between the Olancha Dunes and the playa is partially vegetated, the overall sparseness and patchiness of the vegetation cover—on the order of 10 to 15 per cent—is such that a significant amount of sand (approximately 25 to 50 per cent) would be able to pass through the vegetated zone (Buckley, 1987).

The second area of high sand motion is located north and west of Keeler and south of Swansea on the northeastern sand sheet. This area obtains its sand supply primarily from a field of young, partially vegetated sand drifts and dunes along the lakeshore (the Swansea dunes), as well as from lacustrine sediments formerly deposited by longshore drift and flow through the Owens River Delta. A small amount of sediment is also shed off alluvial fans draining the White-Inyo Range to the northeast. This region appears to be the primary source area of many dust events during the autumn (Reid *et al.*, 1994).

Transport of saltating particles. Results of mass collected from the BSNE saltating particle samplers indicated, as in other studies (Goossens, 1985; Zobeck and Fryrear, 1988), that there is a significant concentration of saltating particles near the surface (Table II): approximately 50 per cent of the total mass collected during March 1993 was contained in the samplers at a height of 10 cm, 80 per cent of total mass was collected at or below 20 cm above the playa surface, and over 90 per cent within the first 30 cm. Only a few per cent of the total mass of saltating particles was captured at 1 m above the surface. This effect was more pronounced during the smaller storms. Over 80 per cent of the total saltating particle transport during the month of March 1993 took place in the two major events of 11 and 23–24 March.

Episodes of saltating particle motion over the study site track extremely well with episodes of high wind speeds. Figure 3 shows the saltating particle mass and wind speed plotted on the same time scales. Saltation transport is high only when winds exceed about 4 m s^{-1}.

No intensive spatial profiles were made of saltating particle motion during the March 1993 field experiment, but measurements were made in April and May 1993 in a large rectangular area (1·2 by 2·2 km) on the south sand sheet of Owens (dry) Lake, overlapping the southern end of the LODE intensive test plot. Saltating particles captured along a linear array of Weaver samplers (Ono *et al.*, 1994) parallel to the LODE array, summarized in Figure 4, represent a time period when the sand sheet was uniformly covered by loose sand under and around broken salt-silt-clay crust. There was only a small variation in the amount of sand captured from one end of the test area to the other, regardless of wind direction. Note how the amount

Table II. Total mass of saltating particles captured in BSNE samplers, Owens (dry) Lake south sand sheet, March 1993. Data represent eight dust events, seven sampling sites, at six heights above playa surface

Height above playa surface (cm)	Total mass of saltating particles captured (g)
10	8095·9
20	4659·3
30	1621·3
50	1323·7
60	767·6
100	398·4

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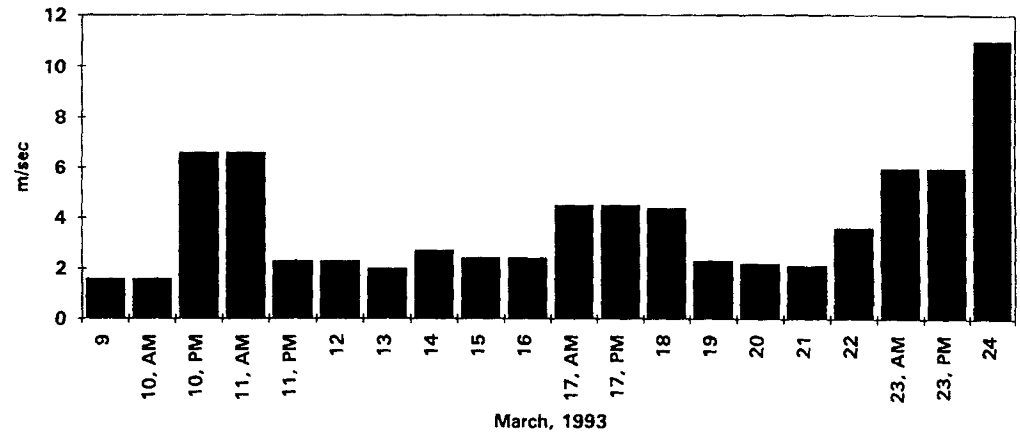

Saltating Particle Transport

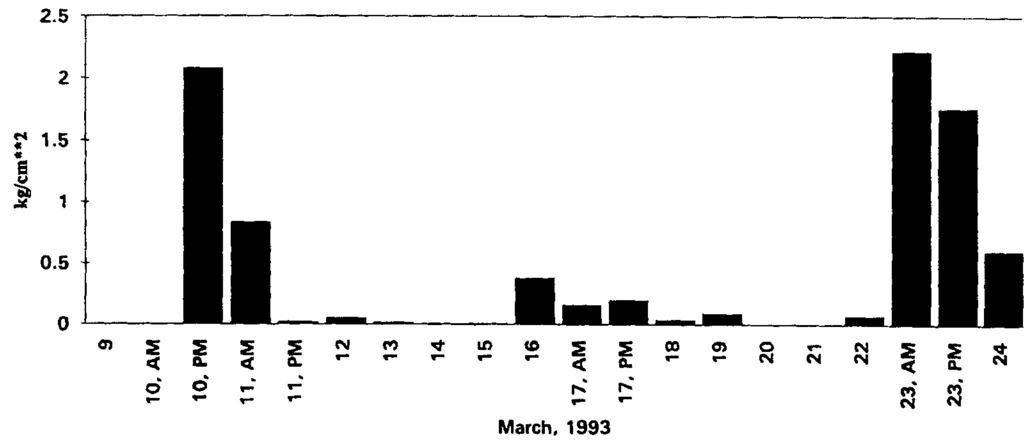

Figure 3. Intercomparison of average daily wind velocity at 2 m height and saltating particle transport Lake Owens Dust Experiment, March 1993

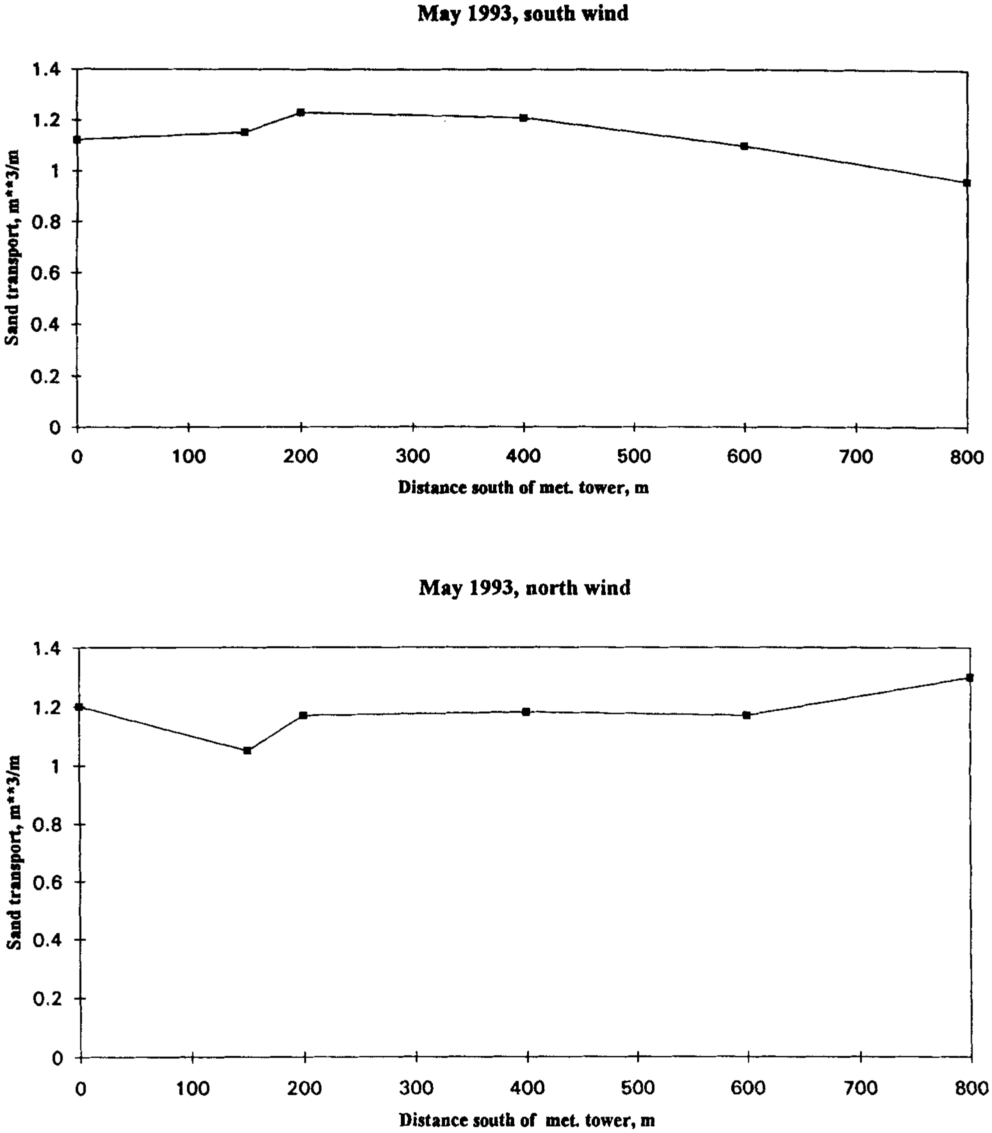

Figure 4. Sand transport in Weaver samplers (Ono *et al.*, 1994) on a north–south line across Owens (dry) Lake south sand sheet, May 1993, at six different sites: (a) S to N, (b) N to S

of sand moving from S to N or N to S is similar. These results are consistent with other LODE data (Gillette *et al.*, 1996), which showed virtually no gradient of sand transport with linear distance for the south sand sheet.

Dust measurements on the playa: aerosol sampling

On the lake bed, the 26-day study included eight days with significant dust events. The four largest storms occurred on 11, 17, 23 and 24 March 1993. Four somewhat smaller dust events were recorded over the lake bed, where the plumes dissipated within 30 km of the playa edge. Except for the afternoon of 24 March, almost all of the dust was generated on the main dust-producing areas of the south sand sheet. Plumes generated on the south sand sheet had near-surface 1- to 2-h PM_{10} loadings recorded at the shoreline ranging from 500 to 10 000 $\mu g\, m^{-3}$.

On the afternoon of 24 March, the northeastern sand sheet began to produce dust plumes. Short-term (10 min or more) PM_{10} measurements on the shoreline recorded by the mobile unit were in excess of $27\,000\,\mu g\,m^{-3}$, and the concentration of total suspended particles smaller than $15\,\mu m$ diameter exceeded $47\,000\,\mu g\,m^{-3}$. For perspective, the U.S. federal air quality standard for 24-h PM_{10} average is $150\,\mu g\,m^{-3}$, and the U.S. occupational safety and health industrial recommendations suggest dust mask usage when total suspended particulate levels exceed $5000\,\mu g\,m^{-3}$.

The PFS design and minimal siting requirement allowed us to directly sample the plume in the area where it originated on the playa, as opposed to previous studies which could only measure dust concentrations when the plume drifted off the lake bed toward Keeler or Olancha. The March 1993 particulate data (Figure 5) were taken on 10 March (background), 11, 17, 18 and 23 March along the same north–south linear array used for saltating particle monitoring, at four meteorological stations spaced at intervals of 50 m within the array.

In order to assess the overall variability of dust measurements through the array, we compared the aerosol

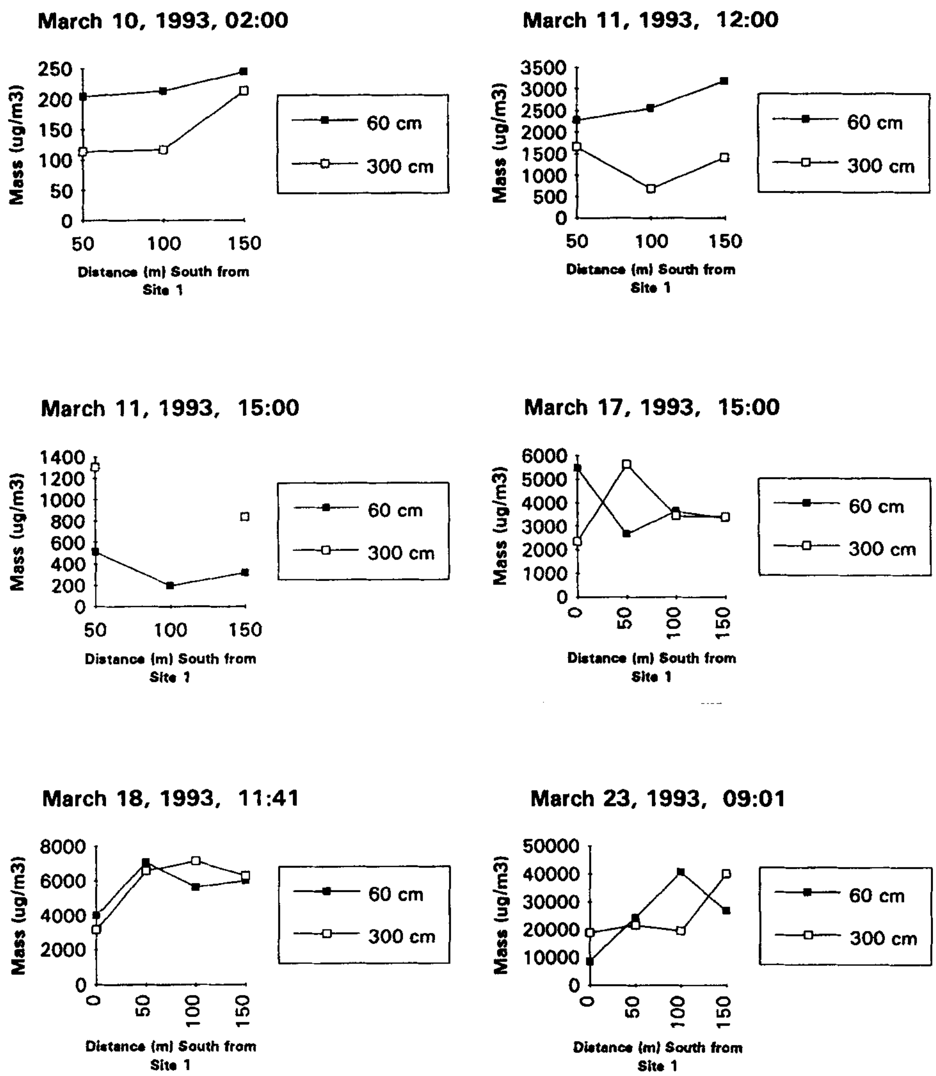

Figure 5. PM_{10} concentrations at two heights during six dust events, Owens (dry) Lake south sand sheet, March 1993

data at the north and south ends of the array to that at the centre (Table III). The variations in dust concentrations from site to site during each dust event are most likely due to variations in the microscale processes controlling the generation, transport and settlement of dust in an active source area, factors which are not seen in measurements of the dust cloud after it has been transported downwind out of the source zone over much larger scales of space and time. The storm-to-storm variations in the PM_{10} concentrations (much greater than an order of magnitude over the course of the study) were significantly greater than either the variation in aerosol mass concentrations through the array in a given event, or the variation in aerosol mass concentrations between top and bottom samplers at each site in a given dust event.

There is a great deal of work to be done in correlating the complex records of meteorology and dust production from this field study, documented in detail by Cahill *et al.* (1994). There was a very poor correlation between winds measured on the array itself and those at Keeler and Olancha on the edges of the lakebed (r^2 for both cases of 0·27), even to the point where wind directions were reversed during some events. Photographs and qualitative observations made by the authors off the playa are at a much larger scale than the array, and thus may not tell much about local conditions. Despite these limitations, we can make the following observations.

1. Photographs indicate complex behaviour of the dust above the site. Plume lofting occurred during most of the dust sampling periods; in some cases, dust rose hundreds of metres at very steep angles in a matter of minutes.
2. The measurements of 10 March at 02:00 and 11 March at 12:00 had winds from the north. Very minor dust production took place on 10 March, but on 11 March moderate dust production was noted at the sites during the sampling period.
3. On 11 March at 15:00, the winds were initially from the north. This resulted in light dust production during the sampling period. One sample was lost due to operator error.
4. On 17 March at 15:00, winds from the WNW resulted in moderate dust production at the sampling array. The array was lined up north–south, so the results must be corrected for wind direction effects.
5. On 18 March at 11:41, the winds at the site were from the north at the initiation of sampling, but the regional winds were from the south according to the remote sensing camera logs and our observations. The wind flow pattern was complicated, and the array appears to have been in a localized eddy of wind-carrying dust, kilometres in extent. Powell and Klieforth (1991) described the existence of such cyclonic, topographically generated eddies over Owens (dry) Lake, typically in late winter or spring, which can produce the observed conditions of north wind at the study side and south winds at Keeler.

Table III. PM_{10} mass concentrations ($\mu g\,m^{-3}$) at each site, elevation and sampling period, Lake Owens Dust Experiment, March 1993. T = top sampler (300 cm above playa), B = bottom sampler (60 cm above playa): sites are 50 m apart on the playa of the actively eroding south sand sheet

Site	March 10 02:00 2 h	March 11 12:00 1 h	March 11 15:00 2 h	March 17 15:00 1 h	March 18 11:41 1·5 h	March 23 09:01 2 h
1 (north end)				T = 2350	T = 3137	T = 18740
				B = 5462	B = 4000	B = 8545
2	T = 133·3	T = 1667	T = 1303	T = 5620	T = 6569	T = 21560
	B = 203·7	B = 2284	B = 511·1	B = 3309	B = 11980	B = 36640
3	T = 116·7	T = 691	T = 304·2*	T = 3442	T = 7132	T = 19470
	B = 213·0	B = 2549	B = 195·8*	B = 3646	B = 5646	B = 40620
4 (south end)	T = 213·0	T = 1414	T = 835·1	T = 3407	T = 6277	T = 39950
	B = 243·8	B = 3167	B = 313·3	B = 3347	B = 6014	B = 26770
(site 2 + site 3) (site 1 + site 4)	0·70	0·78	1·00*	1·00	1·61	1·26

* Spurious value due to operator error

Our reconnaissance of Owens (dry) Lake over several years confirmed that local winds sometimes flow cyclonically around the playa.

6. On 23 March at 09:01, the winds were from the south. The increase in concentration with distance downwind is probably a manifestation of the fetch effect (Cahill *et al.*, 1994; Gillette *et al.*, 1996).

The PM_{10} data from the active dust generation zone on the playa (Figure 5, Table III) show that the amount of dust increased rapidly during the month of March. They match the near-instantaneous breakdown of the efflorescent crust followed by the steady destruction and disaggregation of the more resistant salt-silt-clay crust with subsequent release of fine, wind-erodible materials. The mean dust concentrations rose from 1961 $\mu g\, m^{-3}$ on the morning of 11 March to 26 536 $\mu g\, m^{-3}$ on the 23 March for wind velocities and saltating particle fluxes of the same magnitude. This appears to confirm the role of crusts in suppressing the generation of PM_{10} dust.

The mean dust levels can be used to characterize dust production at the array sites, averaging the concentrations at 60 and 300 cm sampling heights together as we have done in the bottom row of Table III. The dust concentration was roughly uniform along the array, considering that this was a natural system with inherent small-scale inhomogeneities in the active dust generation process, with the ratio of the centre two sites to the end sites ranging from 0·70 (11 March, a.m.) to 1·61 (18 March). This was not anticipated, since the crust was being actively degraded from south to north across the array. In the earliest dust events (i.e. 11 March), the south end had lost more of its crust than the north end, but a low gradient in dust concentration was observed. This supports the hypothesis that the direct entrainment of the crust itself was not a major source of aerosols. The abrasion of this crust into a finer powder by the sand motion/saltation process provided the strongest source of PM_{10} at the Owens (dry) Lake site.

We can also begin to investigate the vertical gradients of PM_{10}. In the first two measurements of 10 and 11 March, a period where efflorescent crust was mostly intact, the low level (bottom) air samplers received a greater loading of dust than did the upper level (top) samplers. This is the expected behaviour when a dust source is in the immediate vicinity and slightly upwind of the sampler, since this produces a vertical gradient into relatively cleaner air above. These measurements further confirm that the source was local during these dust events.

The situation of the late afternoon of 11 March is the converse. In this case, the upper (300 cm) samplers had more dust than the lower (60 cm) samplers. This behaviour is expected when a source is well upwind of the sampler and the area near and below the sampling location is a stronger sink than a source. As there is always a removal rate associated with the deposition velocity, the removal sink dominated the local source in this example. On 11 March, an intense dust storm started in the morning on the south sand sheet, and then spread over a large part of the playa in the afternoon. Wind direction shifts took place, and the wind velocity decreased as time passed. Hence, as the storm wound down and the local source ceased to be active, there was an inversion in the vertical dust gradient. These measurements are among the few direct confirmations of this process.

In the remaining three dust events, no significant vertical gradients were seen in the samplers, indicating a balance between dust sources and sinks at the site. The precision of the samplers degraded during these measurements, however, so that caution should be expressed when reproductibility may be in the range of 20–40 per cent.

The interrelationship of meteorology, playa surface conditions, and dust generation

Figure 6 shows the mean wind velocity at 2 m above the playa on the GEOMET tower, the percentage of efflorescent/salt crust exposed, and the derived friction velocity during wind erosion periods (Gillette *et al.*, 1996) from the LODE array. The data shown represent the 'active period' of the measurement, such as the high wind velocities on the morning of 11 March, which decreased in the afternoon. The mean wind velocity was similar for the storms of 11, 17, 18 and 23 March. The destruction of the efflorescent crust occurred quickly, in 2 to 3 h on 11 March, and the remaining salt-silt-clay crust was slowly eroded and covered with clasts (including its own broken pieces) during the remainder of the study.

Figure 7 shows how these conditions influenced sand transport and dust production. The sand transport

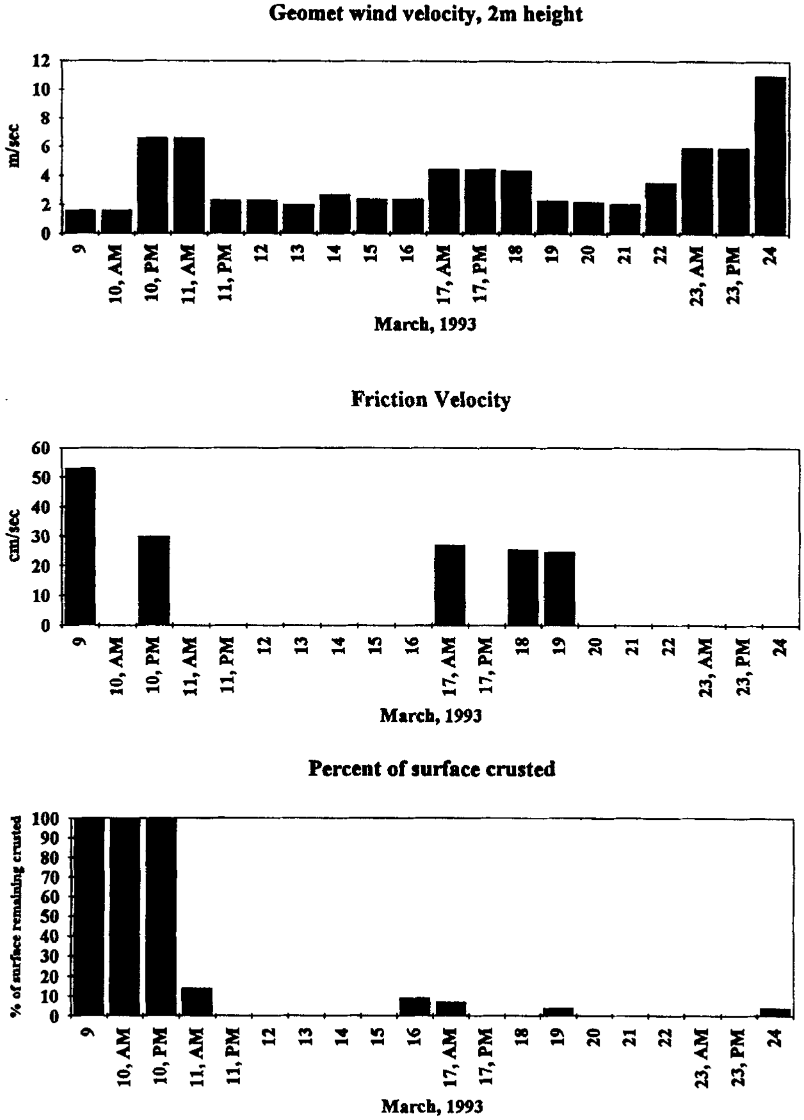

Figure 6. Intercomparison of average 2 m wind velocity at GEOMET site (top), average friction velocity during erosion periods (centre) and average percentage of surface in study plot remaining crusted (bottom), Owens (dry) Lake, March 1993

data mimic to some degree the dust production of Figure 5, but the PM_{10} dust production averaged along the array and at both the high and low samplers, has a very different behaviour, rising steadily throughout the period. The relation between the logarithm of PM_{10} aerosol production and saltating particle mass (Figure 8) shows that despite high winds and sand motion on 11 March, little dust was generated as the efflorescent crust broke up. Over the next two weeks, every storm was more and more efficient in producing dust by abrading the salt and silty components of the lake bed.

Figure 9 shows the relations between the logarithm of the ratio of PM_{10} dust to saltating particle transport and the percentage of exposed crust (taken on a given date during the study). There are many reasons why the relationship is not exact, since PM_{10} is a regional effect while the dust motion is local, yet a good logarithmic regression was achieved. The uncertainty of the final two data points of 18 and 23 March was as high as ± 20 per cent, making exact comparisons unlikely. Recent tests at Mono Lake by GBUAPCD with their

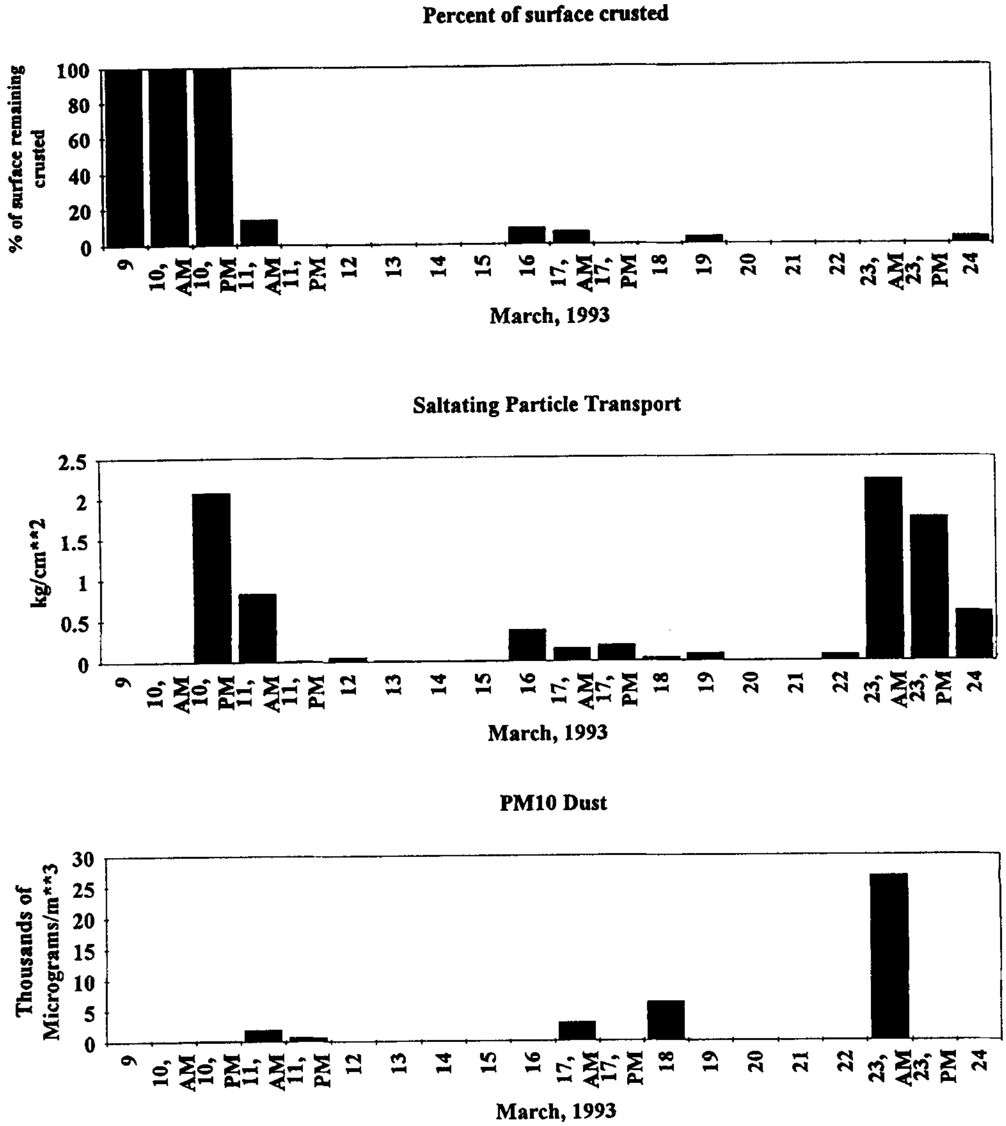

Figure 7. Intercomparison of percentage of surface in study plot remaining crusted (top), saltating particle transport across plot (centre), and average PM_{10} concentration across plot (bottom), Owens (dry) Lake, March 1993

wind tunnel also showed orders of magnitude variations in dust production rates at various sites and times (E. Hardebeck, pers. comm., 1993).

The physical process behind the increasing dust production per unit sand motion is most probably the destruction of weak adhesions between silt and salt by the abrading sand. This suggests the use of a mechanical parameter in the description of dust production. We propose here the use of the term 'sand run', a term used in sub-aqueous transport of sand (Meyer, 1972). We define sand run as saltating particle transport ($kg\,m^{-2}$) times wind run (km) (defined as average wind velocity for a given time period multiplied by that time period, $km\,h^{-1}\,h$); it represents both the mass of saltating sand grains that crosses an area and the total distance the grains have travelled across the surface. Figure 10 represents the data in this format. Sand run has a close connection to the parameter Q (mass flux) used in the description of the fetch effect (Cahill *et al.*, 1994; Gillette *et al.*, 1996). It is clear that until the surface playa crust is destroyed, dust production is minimal. After that point, the logarithm of the ratio of dust production to sand motion is proportional to sand

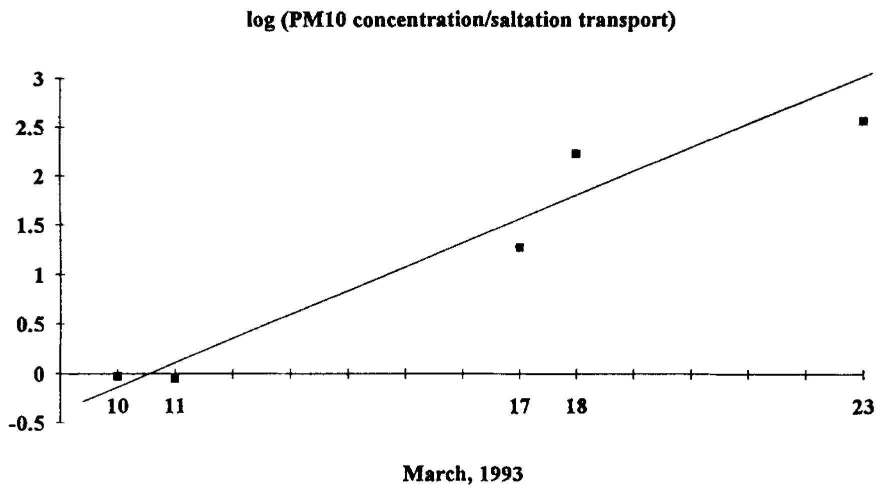

Figure 8. Variation of the logarithm of (average PM_{10} concentration across plot/saltating particle transport across plot) with date, Lake Owens Dust Experiment, March 1993

run, with an r^2 of 0·98. This is also in agreement with the work of Hsu (1974, described in Pye and Tsoar, 1990, pp. 114–116), who used field data from several sites to show a log-linear relationship of sand transport rate and wind run. While the significance of our observations is not yet completely understood, the relationship that exists and the analogous effect noted by other workers may be helpful in developing models to predict the sand transport rate from dust production data and/or vice versa.

SUMMARY

We performed a sequence of field and laboratory work to determine the conditions that initiate Owens (dry) Lake dust events and how they relate to the conditions on the Owens playa itself. The nature of aerosol

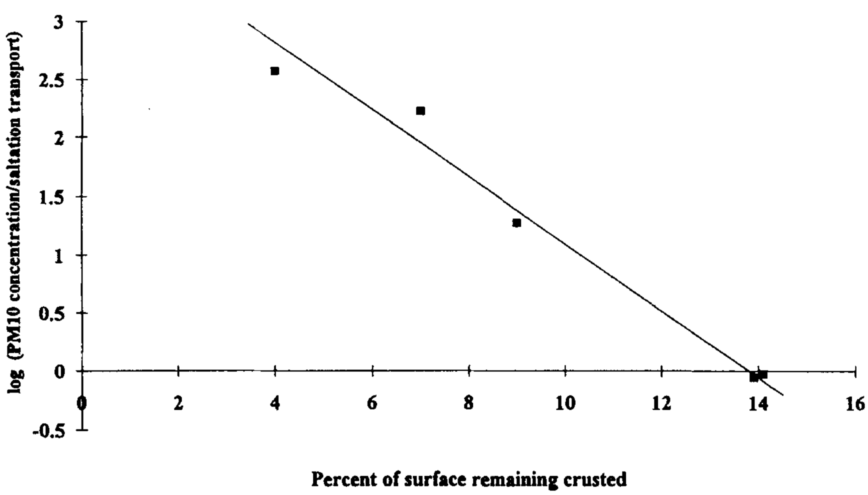

Figure 9. Variation of the logarithm of the ratio (average PM_{10} concentration across plot/saltating particle transport across plot) with percentage of surface in study plot remaining crusted, Lake Owens Dust Experiment, March 1993. r^2 of line is 0·97

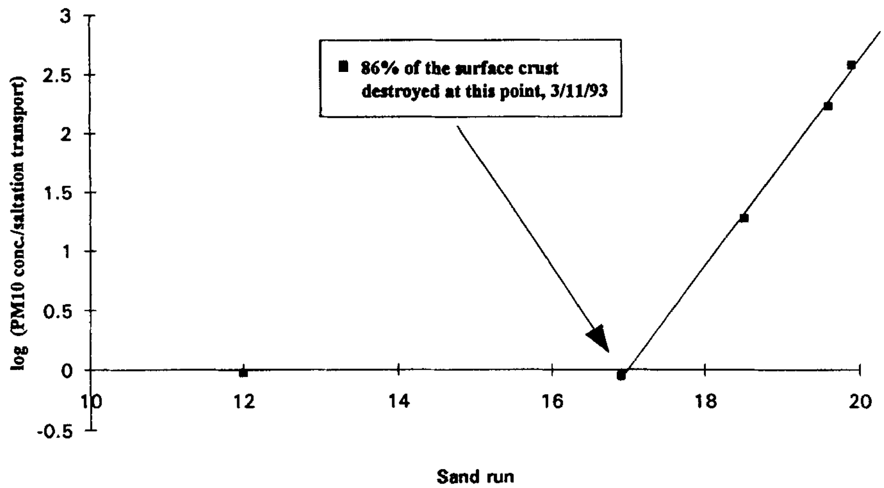

Figure 10. Variation of the logarithm of (average PM_{10} concentration across plot/saltating particle transport across plot) with sand run (saltating particle transport ($kg\,m^{-2}$) multiplied by wind run (km)), showing apparent linearity of the relationship after destruction of the efflorescent surface crust, Lake Owens Dust Experiment, March 1993. r^2 of line is 0·98

sources and generation was determined by reconnaissance of playa surface conditions, extensive aerosol monitoring, and a large set of meteorological data.

The saltating particle motion and dust aerosol measurements of the March 1993 LODE study have provided the first detailed study of the processes that generate the Owens (dry) Lake dust storms and the first detailed measurements of dust concentrations and small-scale variations within an actively emitting playa source area. To the best of our knowledge, the dust levels on the lake bed on 23 March 1993 represent the highest PM_{10} concentrations measured to date in North America. The results clearly show that there is no substitute for actually making the measurements on the lake bed during dust storms, despite all the effort such measurements entail.

We documented the rapid destruction of the fragile efflorescent crust in a period of less than 3 h on 11 March 1993. This left behind a more stable salt-silt-clay surface which is not easily subject to wind erosion. Subsequent storms, however, began degrading this crust, developing a thin sand layer that was rapidly mobilized in strong winds, and able to generate PM_{10} dusts by the saltation–abrasion mode. Once this occurred, the threshold wind velocity for dust events dropped sharply, and dust storms became large and more common. The most important conclusion which can be drawn from these data is that the motion of sand across the playa and the subsequent pulverization of playa surface materials by saltating particles are the most important factors in the generation of fine dusts from Owens (dry) Lake.

The data gained from this study will be useful for understanding the connection between dust in the atmosphere and local and regional meteorological conditions, the mechanisms and persistence of dust transport, and the characteristics of sediments transported during playa-derived dust storms (with implications for PM_{10} and other pollutant monitoring/estimation). This project made a careful link between aerosol and meteorological measurements, which will improve the modelling of playa-generated dust storms in terms of particle transport versus distance from source.

The implications of this study to dust mitigation are numerous. The most important is that any method that prevents break-up of crusts by saltating particles will consequently greatly reduce PM_{10} dust. We are in the process of using sand fences at Owens (dry) Lake for this purpose, and early results are very promising (Cahill *et al.*, 1994). We then propose to accelerate the establishment of native vegetation on the stabilized dunes that form on and adjacent to the fences, resulting in an ecologically stable, relatively dust-free environment.

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